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WOOD AND OTHER RENEWABLE RESOURCES

A comparison of the GHG emissions caused by manufacturing tissue paper from virgin pulp or recycled waste paper

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Abstract
Purpose The aim of this work is to compare greenhouse gas (GHG) emissions from producing tissue paper from virgin pulp (VP) or recycled waste paper (RWP). In doing so, the study aims to inform decision makers at both company and national levels which are the main causes of emissions and to suggest the actions required to reduce pollution.
Methods An attributional life cycle assessment (LCA) was performed in order to estimate and compare the GHG emissions of the two processes. LCA allows us to assess how the choice of raw material for VP and RWP processes influences total GHG emissions of tissue paper production, what are the main drivers behind these emissions and how do the direct materials; energy requirements and transportation contribute to the generation of emissions. The cradle-to-gate approach is carried out.
Results and discussion The results show that demands for both thermal energy and electricity are higher for the RWP than for the VP if only the manufacturing stages are considered. However, a different picture emerges when the analysis looks at the entire life cycle of the production. GHG from the VP are about 30 % higher than the RWP, over the life cycle emitting 568 kg CO_2 eq more per kilogram of tissue paper. GHG emissions from the wood pulping alone were 559 g CO_2 eq per kilogram of tissue paper, three times higher than waste paper collection and transportation.
Conclusions In terms of GHG emissions from cradle to gate, the recycled process less intensive than the virgin one for two reasons. First, as shown in the results the total GHG emissions from RWP are lower than those from VP due to relatively lower energy and material requirements. Second is the non-recyclability nature of tissue paper. Because the tissue paper is the last use of fibre, using RWP as an input would be preferable over using VP. The environmental profile of the tissue products both from RWP and VP can be improved if the following conditions are considered by the company. First, the company should consider implementing a cogeneration unit to simultaneously generate both useful heat and electricity. Second, it may consider changing the VP mix, in order to avoid the emissions associated with long distance transpiration effort. Third, there is the option of using sludge as fuel, which would reduce the total fossil fuel requirement.

Keywords Greenhouse gas emissions · Recycled waste paper · Tissue paper · Virgin pulp

1 Introduction

The increasing trend of population mainly in developing countries and a high level of consumption in industrialised countries are among the main drivers behind the rapidly increasing demand for natural resources and the associated greenhouse gas (GHG) emissions (European Environment Agency 2010a). There are concerns about unsustainable production and consumption patterns all over the world as various scientific studies provide evidence of the increase in human-related GHG emissions (IPCC 2007; United Nations 1992, 2002).

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The pulp and paper producing industry is the fourth largest GHG emitter among global manufacturing industries and is responsible for around 9 % of the total overall CO_2 emissions from manufacturing industries (Environmental Paper Network 2007; International Energy Agency 2007). The increase in paper consumption is the main driver behind the growth in the sector which results in having large ecological footprint on the planet (Environmental Paper Summit 2002). According to the Organization for Economic Cooperation and Development (OECD; 2008), this demand-driven growth is projected to be at the rate of 2.3 % a year in the coming decades. The consumption of paper varies around the globe and it is correlated with income level. The USA and Western Europe are by far the biggest consumers of paper per capita, 334 and 202 kg per person per year, respectively (Environmental Paper Network 2007). In addition to the burden placed on the environment due to resources extraction and production processes, the unsustainable consumption of paper creates an important amount of municipal solid waste. Again according to the OECD (2008), waste from paper and paperboard make up 21 % of the total municipal waste generated in Spain, which means that the fraction of paper waste is second only to the fraction of organic waste (49 %). Therefore, policy measures that ensure not only a reduction of paper consumption but also an increase of using recycled waste paper (RWP), the implementation of cleaner production practices and the use of fibres from sustainable sources may be of great importance if the climate change impacts of the sector are to be significantly reduced (Environmental Paper Summit 2002).

The pulp and paper manufacturing process has important features that attract the attention of environmental researchers (Szabó et al. 2009). The first one is its high energy consumption and, therefore, its high emissions. In terms of energy consumption, the sector ranks alongside other energy intensive sectors such as cement, iron and steel (Environmental Paper Network 2007; International Energy Agency 2007). The second feature is the sector's intensive use of natural resources. One of the most important input materials in the paper making process is biomass from wood and other fibre sources such as annual plants. Thus, the future of forest lands is directly linked to the production of paper, given that 40–42 % of all wood harvested globally for industrial use is used by the sector (Environmental Paper Network 2007). Recently, RWP has emerged as an alternative to virgin wood pulp as a consequence of ambitious recycling policies (European Union 2008) and technical advances in the paper production process. For example, in Spain the recycling rate [1] has reached 79 % in 2010 from 48.6 % in 2000 according to Asociación Española de Fabricantes de Pasta, Papel y Cartón (2011). The third feature of the paper production process that attracts researchers is the energy self-sufficiency of the paper making process. Despite the fact that the sector is energy and resource intensive, important environment improvements have recently been achieved by the introduction of combined heat and power (CHP), which allows the sector to improve its energetic profile and reduce its use of natural resources.

To date, various studies have investigated the general environmental impacts of pulp and paper production (Cui et al. 2011; Dias et al. 2007; González-García et al. 2009; Hong and Li 2012; Jawjit et al. 2006, 2007; Lopes et al. 2003; Merrild et al. 2009) and the effect of waste paper recycling compared with other waste disposal alternatives (Arena et al. 2004; Björklund and Finnveden 2005; Finnveden and Ekvall 1998; Finnveden et al. 2005; Merrild et al. 2008; Ross and Evans 2002). Only few efforts have been made to study the comparative environmental benefits of using RWP and virgin pulp (VP) for tissue paper. A work from the Environmental Resources Management (2007) investigated the environmental performance of multiple types of tissue products manufactured by Kimberly Clark and assessed the environmental trade-offs associated with the use of VP and RWP. The main findings for the study show that there are no environmental benefits of using RWP over VP or vice versa, as both provide environmental advantages and drawbacks. Specific to global warming impact, tissue paper that contains high VP has relatively lower impact than tissue paper with high recycled fibre content, which is contrary to the result we have obtained. Hohenthal and Behm (2008) also performed a life cycle assessment (LCA) analysis to assess the carbon footprint of toilet tissue paper made from 100 % fresh fibre pulp and 100 % recovered fibre pulp. The analysis is based on three scenarios: allocating 8.6 and 19.6 % environmental burden of the waste papers' first life to the recycled paper and without allocating previous life cycle burden (cut-off). The carbon footprint results are almost the same for fresh fibre and recovered waste fibre in all cases. The slight variation mostly depends on the choice of the burden for the previous life cycle of the recovered fibre. When the cut-off method is applied to assume that the recovered fibre is not responsible for the environmental burden from the previous product's life cycle, tissue paper from recovered fibre has a lower carbon footprint (1.3 kg CO_2 eq per kilogram of tissue paper). However, when the burden from the life of the previous product is allocated to the recovered fibre then it will have higher carbon footprint than the fresh fibre.

In this article, we use real data from Gomà-Camp S.A.U, a tissue paper manufacturing company in Tarragona, Spain, to investigate the GHG emissions associated with the production of tissue paper from both VP and RWP in 2010. The study deals with the following questions: How does the choice of raw materials for the VP and RWP influence the life cycle

[1] Recycling rate is defined as the ratio of the total consumption of recovered paper as a raw material by industries to the total consumption of paper and paper board.

GHG emissions of tissue paper production? What are the main drivers behind the emissions? What is the contribution of the direct materials, energy requirements and transportation to emissions generation? All these aspects are analysed by considering all the stages involved in the life cycle of tissue paper production and identifying the processes that make the most significant contribution to the overall GHG emissions of the product. This kind of analysis highlights where attention must be really focused so that decision makers at both company and national levels are aware of the main causes of the emissions and can take the necessary policy actions.

The rest of the paper is organised as follows: the Section 2 explains the methodology used to estimate the GHG emissions associated with tissue paper production from both raw wood and waste paper. The third section is devoted to analysing and discussing the results, and the final section contains the conclusions and the policy implications of the research.

2 Methodology

The LCA framework according to ISO 14040 and ISO 14044 was the methodology used to compare GHG emissions from the VP and RWP processes (ISO 2006a, b). LCA is the most commonly used tool for evaluating the environmental impacts of specific products (Cederberg and Mattsson 2000; Guinée et al. 2001). In recent years, LCA has emerged as a leading policy instrument in business decision-making processes, in research and development (R&D), in the environmental improvement of products, and in product labelling and environmental declarations, to name but a few. LCA allows the most polluting phases in a product's life cycle to be identified and also provides both an overall environmental evaluation and a detailed analysis of each step, thus preventing changes from being made at a given stage with no regards to the overall life cycle impact. By applying LCA, it is possible to analyse both the material and energy requirements and the associated emissions at all stages of a particular product or service from the extraction of materials, through to the production processes, the use of the product and its final disposal either by reuse, recycling, or in a waste management stream. Such a complete LCA of a product is often referred to as a cradle-to-grave analysis. However, LCA can also be applied to selected boundaries of product systems, for example from materials extraction to production processes, a method known as cradle-to-gate analysis.

2.1 Goal and scope

2.1.1 Aim and scope of the study

The main aim of the study is to determine the GHG emissions that arise from producing tissue paper using virgin or waste paper pulp. In doing so, this study has several outcomes. Firstly, it highlights the most polluting steps during the life cycle of tissue paper produced from both virgin and waste paper inputs. Secondly, it gives an insight into the amount of VP can be saved due to the substitution of waste paper. This enables decision-makers to take more appropriate action to further reduce the environmental impacts of tissue paper. Last but not least, it provides the international LCA community with Spanish data on tissue paper production.

The scope of the study is from "cradle-to-gate"; that is, from the extraction of the raw materials to the processing and manufacturing of the tissue paper. The disposal phases are not covered for two reasons. First, there is a lot of uncertainty regarding the after-use stage of tissue papers because it is not easy to determine whether they are sent to landfill, incinerated or disposed of by any other means. The second reason is that even if we do know the end-of-life, it may be assumed that the GHG emissions associated with the after-use stages of both products would be the same regardless of the origins of the material used to make them.

2.1.2 Functional unit

The principal objective of this work is to determine the GHG emissions of tissue paper products and the trade-offs that could result from using either VP or RWP. Here, it is important to pay attention to the functional equivalency of the products in order to compare their life cycle emissions and to correctly interpret the results. In this regard, both products are considered to provide the same functionality as they are thought to be roughly similar except for slight differences in brightness and dust content. The high quality achieved with tissue paper made from RWP is the result of state-of-the-art technology-intensive processes. Since both products provide the same utility, the functional unit of the system is defined as the production of 1 kg of finished tissue paper.

2.2 System boundaries and systems definition

As we are dealing with tissue paper produced using VP and RWP, we have two distinct system boundaries. The physical and structural property differences between VP and RWP mean they require separate production process lines. Figures 1 and 2 present the details of the main processes included in the production of tissue papers from VP and RWP, and the system boundaries, respectively. For the VP process, we have considered the following processes: wood logging, transportation to pulp mills, extraction and transportation of chemicals for the pulp making process, the pulp making process, transportation of pulp to the tissue paper mill, the tissue paper production process and the treatment of waste from the production process. For the RWP process, we considered the collection and pre-treatment of waste

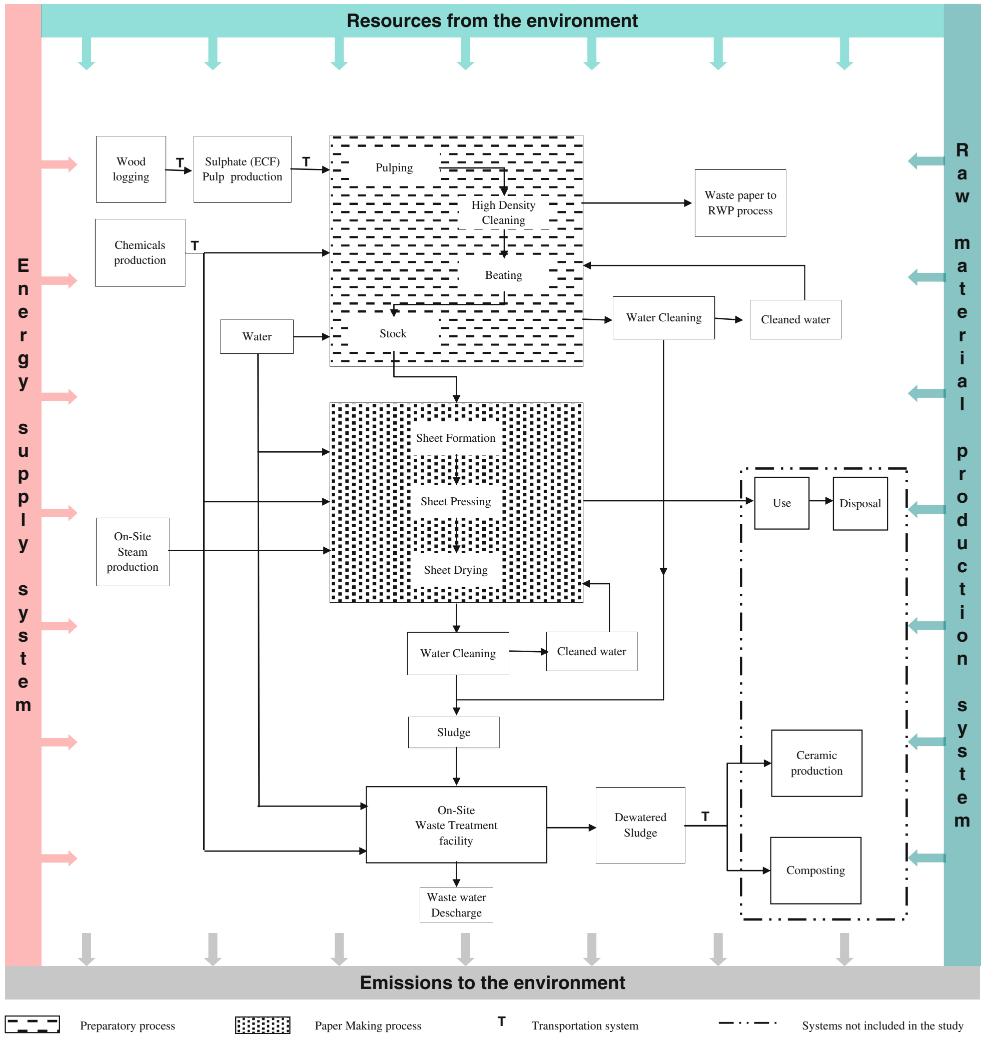

Fig. 1 LCA system boundary and process flows of tissue paper production from virgin pulp

paper, the extraction and transportation of chemicals, the tissue production process and the treatment of waste from the production processes.

2.2.1 Wood logging

Wood logging is the main system considered in the forest operation. Based on the data from ecoinvent woods from both pine (50 %) and spruce (50 %) were considered (Hischier 2007). Logging includes the thinning process, final felling and the extraction of logs.

2.2.2 Pulp making process

The wood pulping process converts wood into fibre for the paper making process. This mechanism comprises highly energy intensive procedures such as debarking, chip refining, cooking, bleaching, washing and drying (Worrell et al. 2008). Pulping processes are broadly classified as mechanical and chemical pulping. Chemical pulping is the dominant process in the pulp and paper industries. It accounts for 75 % of world's wood pulp supply (Das and Houtman 2004). Kraft (sulphate) pulp is the most widely used chemical pulping process. On the basis of the data provided by the company, the present study considers the production of elemental chlorine-free (ECF) sulphate pulp with a bleaching process. The main processes included are: wood handling, chemical pulping and bleaching, drying, on-site energy production, recovery and recycling of chemicals, and internal waste water treatments (Hischier 2007). The VP used in the process is imported from Portugal (68 %), Northern Europe (7 %) and South America (25 %) and similar pulping process is considered for all sources.

2.2.3 Waste paper

There are different sources of waste paper such as waste paper from curb-side collection, direct delivery from industries, secondary packaging, waste from paper production process and waste from printing and converting operations. Different models can be considered depending on the type of sources. For waste papers which are sourced from curb-

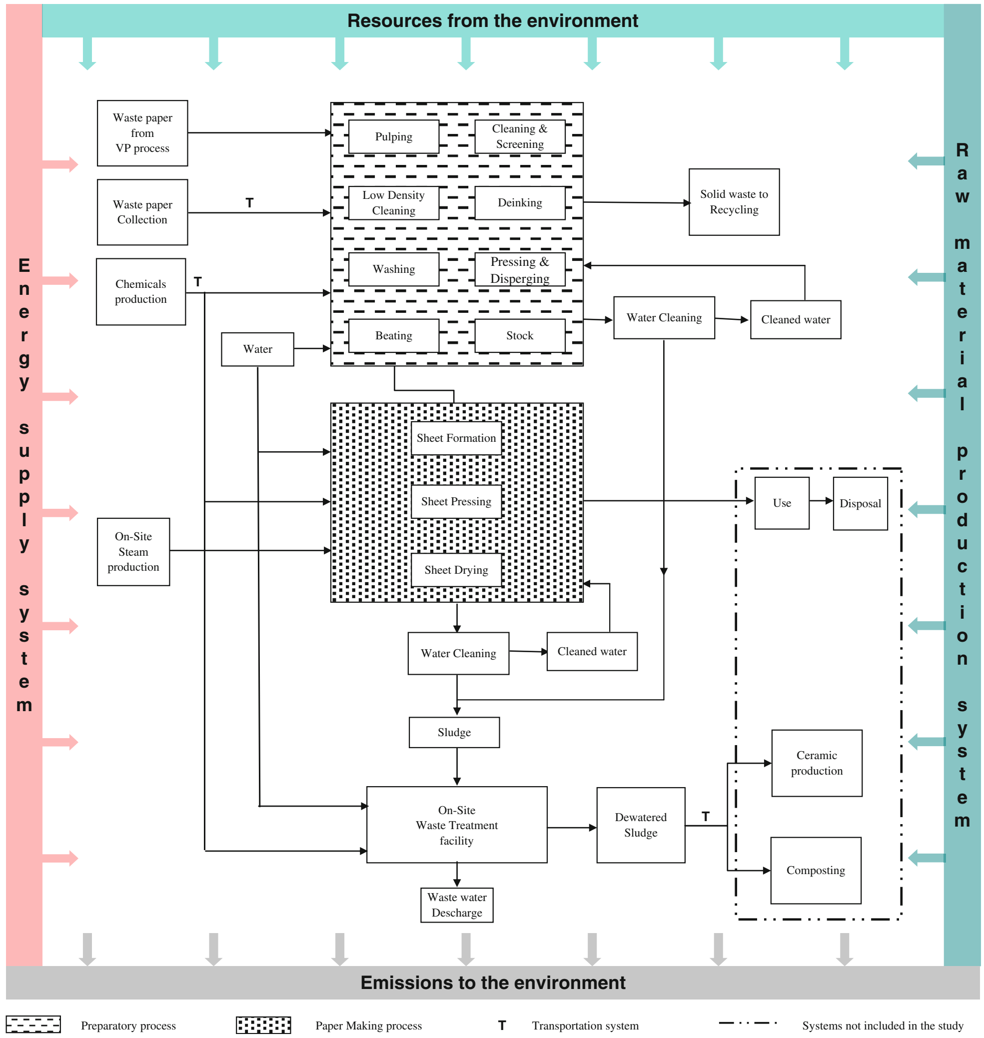

Fig. 2 LCA system boundary and process flows of tissue paper production from RWP

side collection, both the energy and material requirements for the storing process and the subsequent transportation to the factory gate are normally considered. On the other hand, only transportation is considered for waste paper directly collected from industries or the paper producing process and delivered to the paper manufacturing plant (Hischier 2007). Based on the data from the company, the following types of waste paper were identified as the main inputs for the tissue paper making process: mixed office waste (30 %), coated magazine (26 %), white blank news (4 %), light-coloured office waste (8 %) and broken (32 %). Both the energy and material requirements for collection and transportation to the production site are included in the model. The emissions from the use of energy and material for collection and transportation efforts are considered. This allocation is in accordance with the recycled content approximation of GHG Protocol (WRI and WBSCD 2011). The recycled content method assigns the emissions associated with the recycling process to the life cycle that uses the recycled materials, which is tissue paper production process in our case. This approximation is chosen because of the fact that no recycling occurs at the end of life of tissue paper as it is considered as the last stage of the fibre.

2.2.4 Chemicals

Emissions from the extraction and transportation of chemical materials to the chemical industries and the direct emissions from the industries' chemical processes are included (Althaus et al. 2007).

2.2.5 Water

Emissions from the infrastructure and energy used during the treatment and transportation of water to the end user are considered.

2.2.6 Heat production

The extraction and production of natural gas and its distribution and combustion in the boiler at the tissue paper mill are included in the model. The material and energy requirements

and the waste production during all the steps from extraction to combustion and the associated emissions are considered (Dones et al. 2007).

2.2.7 Electricity

The environmental burden associated with the production and transmission of the required amount of electricity is considered. Here, the Spanish electricity production mix for the year 2010 is applied.

2.2.8 Transportation

The LCA considers the emissions associated with the operation of vehicles and ships to transport the pulp, chemicals and other input materials from their respective production sites to the tissue manufacturing gate. It also considers the transportation of waste (sludge) to waste recycling plants (composting and ceramic manufacturing). Furthermore, vehicle operations, emissions from the use of energy and materials during maintenance, disposal of vehicles, and road construction and maintenance are also considered. According to the data provided by the company, around 75 % of the wood pulp is imported from Europe (Portugal (68 %) and Northern Europe (7 %)) by means of lorry. Average road distances of 1,250 and 3,000 km are considered for Portugal and Northern Europe respectively. The VP imported from South America represents 25 % of the total pulp. An average distance of 12,000 km and ship mode of transportation is considered.

2.2.9 Infrastructure

The cut-off rule can be applied in LCA studies in order to avoid unnecessary effort to data gathering when the process, material input or energy input contributes to less than 1 % of the total life cycle emissions. The infrastructure loads are thought to be negligible compared to the environmental burdens from the production process. Therefore, the infrastructure loads in all stages of the production processes are assumed to be of minor importance and have been left out of the analysis.

3 Data sources

Primary data such as the material input requirements for each processing line, i.e. VP and RWP, the electricity and energy demand, and the transportation efforts are based on operational data from Gomà-Camps S.A.U for the year 2010. Detailed information regarding the inventory of the foreground system of tissue production is presented below in Table 1. Extraction and production of ECF sulphate pulp (Hischier 2007), chemicals (Althaus et al. 2007) and natural gas (Dones et al. 2007), and the collection and transportation of waste paper (Hischier 2007) are modelled using secondary data from the ecoinvent database. The quantities of the material and energy inputs and the emissions specified in the inventory table are the quantities required and released during the production of the defined functional unit that is 1 kg of tissue paper.

4 Results

The comparison between the VP and RWP process lines is based only on the GHG emissions resulting from the energy and material requirements for the production of tissue paper. It is important to note that the result would be different if we had also taken into account other environmental impacts such as land use and land use change. In the case of VP process, harvesting forest lands are necessary in order to provide the wood for pulping, while the RWP processing line requires only waste paper as input, so consequently much less land use when compared to the VP. In terms of land use change, because the pulp comes from sustainably managed commercial forests (J. Gomà-Camps, personal communication, February 2012), we consider that there is no deforestation related to providing the wood for pulp production and therefore no related LUC–GHG impacts. In the following, we present the results from analysing the VP production line, followed by the results of the RWP line and comparison of the two lines. The discussion of results is provided in the next section.

Figure 3 shows the GHG emissions associated with each input material and process. The total GHG emissions of tissue paper from VP process were calculated to be 1.9 kg CO_2 eq kg^{-1}. The emissions from the use of materials (pulp and chemicals) account for 32 % of the total. The relative contribution of pulp production is 30 %. The main sources of emissions in the pulp production process are the use of fossil fuels (hard coal, natural gas and heavy fuel oil), the combustion of lime in lime kiln stands, the combustion of biomass, and the chemical recovery units. This is in line with results obtained by other authors, e.g., González-García et al. (2009) and Jawjit et al. (2007). In our calculations, only GHG emissions from nonrenewable sources of fuels are considered. We assume that biogenic carbon emissions are balanced by the carbon fixed by the trees, given that the pulp comes from sustainably grown forests. Emissions from the use of chemicals are relatively low and responsible for only 2 % of the total impact.

Electricity consumption during tissue paper production accounts for 25 % of the total GHG emissions. Electric power is mainly consumed to operate different motor drivers. Processes

Table 1 Foreground system inventory data for tissue production from VP and RWP processes

VP process			RWP process		
From technosphere	Value	Unit	From technosphere	Value	Unit
Biomass					
Pulp	1.1	kg	Waste paper[a]	1.5	kg
Transport, road			Transport, road		
Lorry, 16–32 t	1.2	tkm	Lorry, 16–32 t	1.1	tkm
Transport, ship					
Transoceanic freight	3.2	tkm	Transoceanic freight	–	tkm
Energy			Energy		
Electricity	1.0	kW_eh	Electricity	1.1	kW_eh
NG (heating system)	0.6	kW_th	NG (heating system)	0.7	kW_th
Chemicals					
Soda	0.7	g	Soda	1.3	g
Organic chemicals	0.5	g	Organic chemicals	5.6	g
Resin	5.2	g	Resin	4.3	g
CO_2 liquid	3.0	g	CO_2 liquid	2.7	g
Urea	0.1	g	Urea	0.6	g
H_3PO_4	0.0	g	H_3PO_4	0.4	g
O_2	4.1	g	O_2	35.3	g
From resource			From resource		
water	6.2	L	water	8.6	L
To technosphere					
Solid waste (recycle)	0	g	Solid waste (recycle)	10	g
Sludge (composting)	80	g	Sludge (composting)	550	g
Sludge (ceramic)	50	g	Sludge (ceramic)	370	g
To environment					
Emissions to water					
AOX	0.2	mg	AOX	0.2	mg
BOD	112.4	mg	BOD	139.6	mg
COD	374.6	mg	COD	465.4	mg
Nitrogen	0.2	ppm	Nitrogen	0.2	ppm
Phosphorus	0.2	ppm	Phosphorus	0.2	ppm
Water effluent	3.8	L	Water effluent	4.7	L

All the inventory data refer to the functional unit of the study: 1 kg of tissue paper production

[a]The fibre input is covered to 100 % byRWP

such as pumping, high density cleaning, refining, paper forming, pressing and finishing operations rely totally on electricity. Unlike most integrated paper mills, there are no on-site power boilers that generate electricity for internal demand; hence, the entire source of electricity is the Spanish national grid, where electricity production is highly dependent on fossil fuels.

Steam and hot air production is also one of the major sources of GHG emissions and contributes to 23 % of the overall result. Most of the steam heat is used in the drying stage of the paper making process. The drying operation is the most costly operation because it requires large amounts of steam in order to evaporate any excess water left over from the pressing operation. Steam heat generation in the mill is entirely dependent on the use of fossil fuel (natural gas).

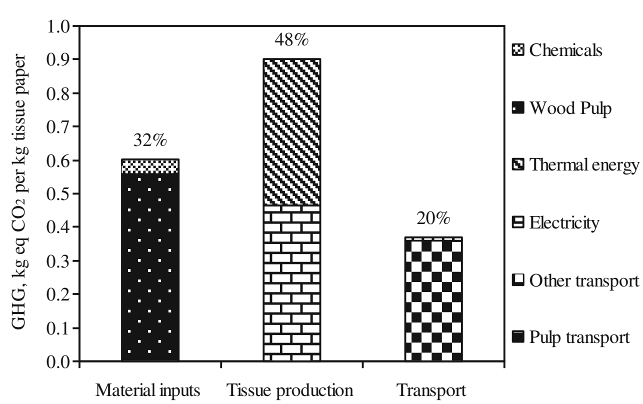

Fig. 3 Contribution to the GHG emissions of inputs during tissue paper production using the VP process

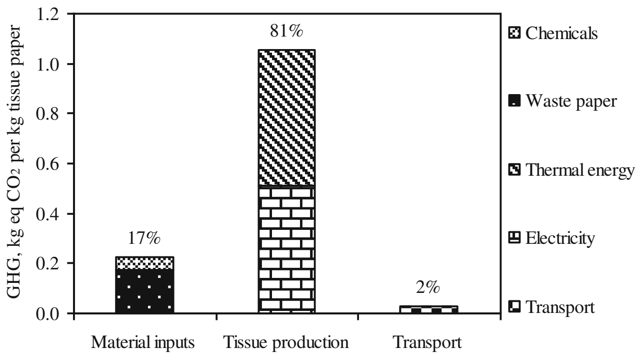

Fig. 4 Contribution to GHG emissions of inputs during tissue paper production using RWP process

Transportation is responsible for 20 % of the GHG emissions. Around 75 % of the total pulp is imported from Europe and the most commonly used form of transportation is by road. The remaining 25 % of the pulp is imported from South America by ships. Although the imported pulp from South America represents only a quarter of the total amount of pulp used, it contributes 40 % of the total transportation related emissions. Even though ship freight transport is the lowest impacting mode of transportation (European Conference of Ministers of Transport 1998), in this case its contribution is relatively high because of the long distance that the wood pulp has to travel.

The GHG emissions from RWP process are presented in Fig. 4. The total emissions that arise from the use of waste paper as a main input in the tissue making process are calculated to be 1.3 kg CO_2 eq kg^{-1}. Production of electricity, steam and hot air are the most important inputs and contribute around 39 and 42 %, respectively, of the total GHG emissions. As with the VP process, electric power from the national grid is used for driving motors in high- and low-density cleaning, screening, refining, paper forming, pressing and finishing operations. Steam is mainly used during the drying operation of the paper making process.

GHG emission associated with waste paper input is responsible for 13 % of the overall GHG emissions. This is due to the fossil fuel required for collecting and transporting waste paper to the tissue production site. The emissions from the use of chemicals represent around 4 % of the total GHG emissions. Chemicals are used both in the paper making processes and in the onsite wastewater treatment plant. The GHG emissions from the transport category come from transporting chemicals both for the paper making processes and the wastewater treatment plant, and from the transportation of dried sludge from the on-site wastewater treatment plant to the final use. An important amount of sludge (1.3 t of dewatered sludge per ton of production[2]) is produced from the treatment plant and it is used as a raw material input in the ceramic industries (40 %) and for composting plants (60 %). The GHG emissions from the transportation represent 2 % of the total emissions. Despite the fact that the relative emissions contribution of treated waste sludge is very small compared with the others, it is highly important economically as it costs the company up to 18€ to dispose of each ton of sludge.

Table 2 compares the GHG emissions for the VP and RWP processes. When only the manufacturing process is considered, the emissions from chemicals, electricity and steam are higher for RWP than for VP. This is mainly because manufacturing tissue paper from RWP process requires a relatively longer process, as can be seen in Fig. 2. Additional processes such as screening, low-density cleaning, deinking, washing, pressing and hot disperging are essential in order to clean and prepare fibre from waste paper for use in tissue production.

When the whole life cycle process is considered, a rather different picture emerges. The GHG emissions from the VP process are roughly 30 % higher than from the RWP process, which implies a saving of 568 g CO_2 eq per kilogram of tissue paper produced. The difference is due to the material and energy requirement for producing and transporting the main input materials. For example, the transportation of pulp from South America and Portugal contributes around 93 % of the total GHG emissions from transportation, whereas the GHG emissions caused by transportation during the RWP process are much lower because the paper waste is supplied by the local market.

In both VP and RWP processes, CO_2 emissions represent around 92 and 91 % of the total GHG emissions in VP and RWP process, respectively. Next to CO_2 is methane that contributes relatively high from non-CO_2 GHG emissions, 6 and 7 % in VP and RWP processes, respectively. The contribution of other GHG emissions such as carbon monoxide (CO), nitrous oxide and sulphur hexafluoride are very low.

It is also interesting to note the saving of trees (pulp) that could be achieved by using waste paper as primary input material to tissue paper making process instead of VP. Substituting used paper for VP can obviously help to reduce pressure on forests and the potential environmental impacts associated with forest operation and pulping processes. Here, the most important issue is how to define the equivalence between VP and RWP. It is clear that a given amount of RWP does not provide the same quantity of tissue paper that can be obtained from a similar amount of VP, assuming that both are used to produce paper of a similar quality. The weight loss in the case of the RWP process is higher than in the VP process because fibre deterioration occurs during the use and recovery of the original paper mainly as a result of contaminants such as mineral charges, inks, plastics and other non-cellulosic materials. Hence, substitution ratio between RWP and VP is always less than one (Merrild et al. 2008). On the basis of yield data from the tissue plant, the output of tissue

[2] Personal communications with the tissue-producing company (2011).

Table 2 Comparison of the GHG emissions for VP and RWP processes

VP process		RWP process	
Process	GHGg eq CO_2 kg^{-1}	Process	GHGg eq CO_2 kg^{-1}
Chemicals	43	Chemicals	52
Electricity	465	Electricity	512
Pulp	559	Waste paper	173
Steam heat	438	Steam heat	541
Transport	368	Transport	27
Water	2	Water	3
Total	1,875	Total	1,307

Functional unit: 1 kg of tissue paper

paper from 1 t of RWP is equal to 0.7 t from VP. Around 87 t of VP could be saved every day as a result of using RWP for tissue paper production, which is equivalent to 1.8 % of the annual VP procurement of the Spanish pulp and paper sector (Asociación Española de Fabricantes de Pasta, Papel y Cartón 2011). Being tissue paper is the last stage of fibre, in which recycling is not possible; the use of waste paper pronounces its advantage over VP.

5 Discussion and concluding remarks

Using RWP instead of VP has implications for various aspects of paper production such as use of water, use of chemicals, energy requirements, the effects on climate change and so on. As this paper estimates only the GHG emissions, we mainly focus on the emissions associated with the use of energy and materials. Here, it is worth mentioning that the biogenic CO_2 emissions are not considered in the analysis. The carbon neutrality of biogenic sources of CO_2 emissions are implemented on the basis that the wood pulp comes from sustainably managed forest. We have also neglected the temporary storage of carbon in the tissue paper, considering the short life span of the tissue paper as compared to other products from wood, such as furniture, buildings, etc. Hence, only the CO_2 emissions which are released from the combustion of fossilised fuel sources were taken into account.

If we consider only the manufacturing process, the energy demand in the form of electricity and thermal energy is relatively higher for the RWP process than for the VP process. But when we compare the entire life cycle, a rather different picture emerges. The total life cycle energy requirement of the RWP process is lower than VP process mainly because the VP process needs more energy to prepare wood chips and transform them into clean lignin-free fibres. This process requires significantly more energy than transforming waste paper into fibres. The energy needed for transportation is also an important element which contributes to the differences observed between the two process lines. A vast amount of fossil fuel energy is required to collect and transport wood from forests to pulp making mills and then to the paper manufacturing site. In this study, around 75 % of the wood pulp is imported from Europe by lorry and around 25 % is imported from South America by ship. In contrast, most of the waste paper comes from the Catalonia area, and covers approximately 250 km during both collection and transportation to the site. The considerable difference between the transportation distances for wood pulp and waste paper means that the associated energy demand for transportation is also significantly different. Our results indicate that substituting VP with RWP reduces significant fossil fuel emissions that arise from the transportation-related energy demands of the VP process.

Further reduction of emissions results when RWP is used to replace pulped wood from forestland, as the recycling of waste paper reduces the demand on forest wood and then eliminates subsequent energy and material requirements of the paper pulping processes. This could also increase forest carbon sequestration because the woods are left to grow to maturity, although such assumption cannot be guaranteed because it totally ignores the possible use of wood for other activities. In practice, when tissue paper is produced from 100 % waste paper, then the pulp that has been saved could be used as an input for producing higher-quality paper that cannot be made from 100 % waste paper. Therefore, recycling waste paper can reduce the sector's overall dependency on forest resources but it does not completely avoid the use of VP as it is not possible to recycle paper ad infinitum (fibres can be recycled no more than seven times). Thus, there are two main environmental aspects to consider when making tissue paper from RWP. The first is the reduction in the total energy and material requirements and the associated emissions. As can be seen from the results, the life cycle GHG emissions resulting from RWP are lower than those from VP. This becomes more important as technological advances allow RWP to be used to obtain paper with the same quality and functionality as that produced from VP. The second aspect is the non-recyclable nature of tissue paper in general. Unlike other types of paper, tissue paper is usually considered to be the last usable stage of the fibres (the end of the fibres' entire life cycle) because they

are unlikely to be further recycled for use in the paper manufacturing process. So they could be used as the purge of the system. This is an important point that highlights the environmental benefit of producing tissue paper from RWP rather than VP. Therefore, if the policy is to reduce GHG emissions, then replacing VP with RWP is the best option for paper tissues production.

From the analysis of these LCA results with the Gomá-Camps company, several areas for improving the environmental profile were identified. Firstly, if the company implements a cogeneration unit (CHP) unit to simultaneously generate both useful heat and electricity the environmental profile of the tissue product both from RWP and VP will be lower than the estimates presented here both in relative and absolute terms. This is because the use of CHP generally reduces energy losses from heat production by increasing the conversion efficiency of the fuel used (up to 93 % of thermal efficiency), thus ensuring a reduction in GHG emissions (about 50 % of the emissions from conventional power generation systems; European Commission 2000). The possibility of on-site power generation will also be of benefit as it totally or partially avoids the use of electricity from the Spanish national grid. Secondly, a change in the VP supply origin can decrease emissions by reducing the emissions from transportation. As shown in the results, emissions associated with the transportation of VP from South America are considerably high. Representing only a quarter of the total amount of VP used, it contributes 40 % of the total transportation related emissions (8 % of the total life cycle emissions). Therefore, reducing the import share of pulp from South America and switching to European market will reduce the emissions. However, the availability of supply in the European market, the quality and the price issues are the most important factors that could challenge practicability. Thirdly, the use of dewatered sludge for on-site energy generation. A significant amount of sludge is produced from the on-site waste treatment facilities and they are disposed of in ceramic and composting plant. The company will be both economically and environmentally benefited if the sludge is used as energy source, for the following reasons: it will reduce the total requirement of fossil fuels and thus avoiding the associated GHG emissions; it also reduce the transportation of the sludge to ceramic and composting plant, which then reduces the emissions due to transportation; and finally the company can also save the money paid for disposing the sludge. Therefore, we are confident that our results give the company a base for future planning and developments which will contribute to its positioning as an environmental leader on the Spanish Market of paper tissues.

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References

Althaus HJ, Chudacoff M, Hischier R, Jungbluth N, Osses M, Primas A (2007) Life cycle inventories of chemicals. ecoinvent report No. 8, v2.0. EMPA. Dübendorf, Swiss Centre for life cycle inventories; Dübendorf, Switzerland. http://ecoinvent.org/. Accessed 19 September 2011

Arena U, Mastellone ML, Perugini F, Clift R (2004) Environmental assessment of paper waste management options by means of LCA methodology. Ind Eng Chem Res 43(18):5702–5714

Asociación Española de Fabricantes de Pasta, Papel y Cartón (ASPAPEL) (2011) Sustainability report (in English). Madrid (Spain). http://www.aspapel.es. Accessed 21 December 2011

Björklund A, Finnveden G (2005) Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies. Resour Conserv Recycl 44(4):309–317

Cederberg C, Mattsson B (2000) Life cycle assessment of milk production—a comparison of conventional and organic farming. J Cleaner Prod 8(1):49–60

Cui Z, Hou Y, Hong J, Ismail Z (2011) Life cycle assessment of coated white board: a case study in China. J Cleaner Prod 19(13):1506–1512

Das TK, Houtman C (2004) Evaluating chemical-, mechanical-, and bio-pulping processes and their sustainability characterization using life-cycle assessment. Environ Prog 23(4):347–357

Dias A, Arroja L, Capela I (2007) Life cycle assessment of printing and writing paper produced in Portugal. Int J Life Cycle Assess 12(7):521–528

Dones R, Bauer C, Bolliger R, Burger B, Faist Emmenegger M, Frischknecht R, Hech T, Jungbluth N, Röder A, Tuchschmid M (2007) Life cycle inventories of energy systems: Results from current systems in Switzerland and other UCTE countries. ecoinvent report no. 5. Paul Scherrer Institut Villigen, Swiss Centre for life cycle inventories, Dübendorf, Switzerland

Environmental Paper Network (EPN) (2007) The state of the paper industry: monitoring the indicators of environmental performance. EPN. www.environmentalpaper.org. Accessed 20 December 2011

Environmental Paper Summit (2002) A common vision for transforming the paper industry: striving for environmental and social sustainability. Drafted by the alliance for environmental innovation, Center for a new american dream, Conservatree, Co-op America, Dogwood Alliance, ForestEthics, the Green Press Initiative, the Markets Initiative, Natural Resources Defense Council, the Recycled Products Purchasing Cooperative. Ratified at The Environmental Paper Summit, Sonoma Country, California

Environmental Resources Management (ERM) (2007) Life cycle assessment of tissue products. report prepared for Kimberly-Clark. Environmental Resources Management

European Commission (EC) (2000) Integrated Pollution Prevention and Control (IPPC). Reference document on best available techniques in the pulp and paper industry. institute for prospective technological studies seville

European Conference of Ministers of Transport (ECMT) (1998) Efficient transport for Europe, Policies for Internalisation of External Costs. ECMT, Paris

European Environment Agency (EEA) (2010a) The European Environment: State and outlook 2010 – consumption and the environment. http://www.eea.europa.eu/data-and-maps/indicators/energy-efficiency-and-energy-consumption-3/assessment. Accessed 05 November 2011

European Union (EU) (2008) Directive 2008/98/EC of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union

Finnveden G, Ekvall T (1998) Life-cycle assessment as a decision-support tool: the case of recycling versus incineration of paper. Resour Conserv Recycl 24:235–256

Finnveden G, Johansson J, Lind P, Moberg Å (2005) Life cycle assessment of energy from solid waste—Part 1: General methodology and results. J Cleaner Prod 13(3):213–229

González-García S, Hospido A, Moreira MT, Romero J, Feijoo G (2009) Environmental impact assessment of total chlorine free pulp from *Eucalyptus globulus* in Spain. J Cleaner Prod 17(11):1010–1016

Guinée JB, Gorée M et al (2001) Handbook on life cycle assessment—operational guide to the ISO standards. Kluwer, Dordrecht

Hischier R (2007) Life cycle inventories of packaging and graphical papers. ecoinvent-Report No. 11, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Hohenthal C, Behm K (2008) Carbon footprint of toilet tissue paper: comparison of toilet tissue using 100% fresh fibre pulp and 100% recovered fibre pulp. Oy Keskuslaboratorio-Centrallaboratorium Ab, KCL Science and Consulting

Hong J, Li X (2012) Environmental assessment of recycled printing and writing paper: a case study in China. Waste Manage 32(2):264–270

International Energy Agency (IEA) (2007) Tracking industrial energy efficiency and CO_2 emissions. IEA, Paris

IPCC (2007) Summary for Policymakers. In: Solomon S, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007 The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK

ISO (2006a) ISO14040 International Standard. Environmental management—life cycle assessment—principles and framework. International Organization for Standardization (ISO), Geneva, Switzerland

ISO (2006b) ISO14044 International Standard. Environmental management—life cycle assessment—requirements and guidelines. International Organization for Standardization (ISO), Geneva, Switzerland

Jawjit W, Kroeze C, Soontaranun W, Hordijk L (2006) An analysis of the environmental pressure exerted by the eucalyptus-based Kraft pulp industry in Thailand. Environ Dev Sustain 8:289–311

Jawjit W, Kroeze C, Soonaranun W, Hordijk L (2007) Options to reduce the environmental impact by eucalyptus-based kraft pulp industry in Thailand: model description. J Cleaner Prod 15(18):1827–1839

Lopes E, Dias A, Arroja L, Capela I, Pereira F (2003) Application of life cycle assessment to the Portuguese pulp and paper industry. J Cleaner Prod 11:51–59

Merrild H, Damgaard A, Christensen TH (2008) Life cycle assessment of waste paper management: the importance of technology data and system boundaries in assessing recycling and incineration. Resour Conserv Recycl 52:1391–1398

Merrild H, Damgaard A, Christensen TH (2009) Recycling of paper: accounting of greenhouse gases and global warming contributions. Waste Manage Res 27(8):746–753

Organization for Economic Cooperation and Development (OECD) (2008) Environmental Outlook to 2030. OECD, Paris. http://www.oecd.org. Accessed June 2011

Ross S, Evans D (2002) Use of life cycle assessment in environmental management. Environ Manage 29(1):132–142

Szabó L, Soria A, Forsström J, Keränen JT, Hytönen E (2009) A world model of the pulp and paper industry: demand, energy consumption and emission scenarios to 2030. Environ Sci Policy 12:257–269

United Nations (UN) (1992) Earth Summit, Agenda 21, UN Conference on Environmental Development, the United Nations programme of action from Rio de Janeiro. UN, Division for Sustainable Development

United Nations (UN) (2002) United Nations General Assembly, World Summit on Sustainable Development: Plan of Implementation. UN, Division for Sustainable Development, New York

Worrell E, Neelis M, Price L, Galitsky C, Zhou N (2008) World best practice energy intensity values for selected industrial sectors. Lawrence Berkeley National Laboratory, Berkeley, CA

WRI and WBSCD (2011) Greenhouse gas protocol (GHGP): product life cycle accounting and reporting standard. World Resources Institute, Washington, DC and World Business Council for Sustainable Development, Geneva